

**Development of a Portable, Ground-based Ozone Lidar Instrument for Tropospheric
Ozone Research and Educational Training**

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Development of a Portable, Ground-Based Ozone Lidar Instrument for Tropospheric Ozone Research and Educational Training

First Year Progress Report

Introduction: Project Objectives

The objective of this project is to develop a portable, eye-safe, ground-based ozone lidar instrument specialized for ozone differential absorption lidar (DIAL) measurements in the troposphere. This prototype instrument is intended to operate at remote field sites and to serve as the basic unit for monitoring projects requiring multi-instrument networks, such as that discussed in the science plan for the Global Tropospheric Ozone Project (GTOP).

This instrument will be based at HU for student training in lidar technology as well as atmospheric ozone data analysis and interpretation. It will be also available for off-site measurement campaigns and will serve as a test bed for further instrument development. Later development beyond this grant to extend the scientific usefulness of the instrument may include incorporation of an aerosol channel and upgrading the laser to make stratospheric ozone measurements. Undergraduate and graduate students have been and will be active participants in this research effort.

Technical Approach

To achieve these goals, emphasis in this project is placed upon the development of (1) all-solid state transmitters which can reliably produce 20-40 mJ pulses in the ultraviolet, (2) a highly efficient, narrow-bandpass receiver, (3) dual analog and photon-counting detector channels, (4) flexible, user-friendly control software, and (5) a mathematical model of the laser transmitter, atmosphere, receiver, and data acquisition system.

This project leverages the significant research accomplishments in the area of lasers and lidar technology by NASA LaRC, Hampton University, and ITT Systems and Sciences. Through technical consultations, equipment loans, and cooperative laboratory work at ITT, NASA, and HU, technologies for this project have been selected and tested.

Moreover, this project is a vehicle through which scientists and engineers at the three organizations can cooperate to achieve the educational program goals of MURED. Through this project, Hampton University students have interacted directly with personnel from NASA and ITT to further their training in NASA-related technologies and science. Five undergraduates, one graduate student, and one postdoctoral researcher (formerly an HU student) have participated in this project.

Research Objectives and Accomplishments for the First Year

1. Evaluation, selection and testing of laser transmitter technologies
 - a. The initial evaluation of candidate lasers was based upon a literature search and technical discussions with industry, university, NASA LaRC, and ITT scientists and engineers. This evaluation reduced the candidates to three: solid state Raman oscillators (SRO's), Optical Parametric oscillators (OPO's), and Titanium-doped sapphire lasers (Ti:S). All of these are pumped by Nd:YAG lasers, are all-solid state, and are reasonably compact and efficient. While uv lasers based upon liquids and gases have been utilized in ozone DIAL systems for many years, these substances are usually awkward to handle, toxic, and require frequent replacement. Sources based on Nd:YAG pump lasers are attractive to NASA for space and airborne applications, since Nd:YAG lasers can themselves be pumped by laser diodes, the most efficient laser pumping technology available. ITT, LaRC and HU scientists had direct

experience with excimer, dye, alexandrite, Nd:YLF lasers as well as these three laser systems and lidar systems based on these lasers, and could make a well-informed evaluation from a system point of view and not just a laser engineering point of view.

- b. These three technologies were under theoretical and experimental evaluation by ongoing research programs at HU, ITT, and NASA LaRC. HU has been pursuing SRO technology since 1995, based upon initial experiments at LaRC. LaRC has been developing Ti:S lasers for almost 10 years, and has successfully demonstrated this laser in the LASE (Lidar Atmospheric Sensing Experiment) system, which autonomously measures water vapor from the NASA ER-2 aircraft. ITT has demonstrated a very efficient OPO technology, based upon work done by Caltech. The laser results are further discussed in the appendices.
- c. At the close of the first year of the grant, an evaluation of the current state of these laser technologies was performed which clearly indicated that the OPO laser technology was the optimal choice at the present time. This decision was based upon the laboratory demonstration of adequate laser energy, technical simplicity, compactness, and cost. However, the development of SRO and Ti:S laser technologies are continuing, and may prove advantageous within a few years.

2. Evaluation, selection, modelling and fabrication of the receiver.

ITT designed the lidar receiver based upon technical requirements defined by HU. They evaluated several possibilities, and selected a highly-efficient grating-based receiver with a square, parabolic primary mirror. A raytrace analysis was performed of the complete receiver optical train in order to quantify the resulting bandpass and spotsize for the receiver. This system is further discussed in the appendices.

3. Selection and testing of data acquisition system and control software

The data acquisition hardware was chosen and purchased based upon the model calculations which showed that dual A/D detection channels plus a single photon-counting channel are required. LabVIEW was chosen as the system software since it could control a variety of data acquisition boards as well as provide for data analysis and display. Its graphical nature makes it particularly easy to learn and implement. See the appendices for hardware specifications and an example of a LabVIEW program written by a student at HU.

4. Development and use of a mathematical model to calculate DIAL system performance and cost-benefit analysis for system design

A complete lidar system computer model was developed, incorporating characteristics of the laser, the atmosphere, the receiver, the data acquisition hardware, and signal averaging. This program was utilized to evaluate the impact of making various technology choices upon the precision of the resulting ozone measurement. In this manner, a cost-benefit analysis could be performed in order to guide the system design so that scientifically useful measurements can be made with the least cost. The parameters utilized in the system model as well as model results are presented in the appendices.

Educational Objectives and Accomplishments for the First Year

1. Training of students in laser remote sensing techniques and atmospheric science

- a. During the 1997-1998 academic year, Roosevelt Elivert (EE) and Brandi Thomas (physics) performed research projects in lidar data acquisition, LabVIEW programming and the importance and chemistry of tropospheric ozone. This led to their presentation at the third annual Hampton University Undergraduate Science Day.
- b. During the summer of 1998, five undergraduates were taught a course in atmospheric science and the remote sensing of ozone using lidar as part of their summer research programs. Three of these students were part of Hampton University's AURORA

(Advanced Undergraduate Research Using Optical Radiation in the Atmosphere) summer program in atmospheric science, and one was part of Hampton University's UniPhy-REU (Undergraduate Institute in Physics-Research Experiences for Undergraduates) program. Their presentations at the close of these programs are listed below.

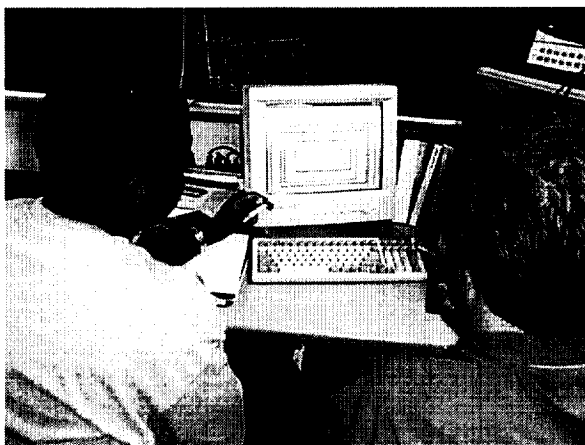
- c. As part of their summer research, three undergraduates attended the 19th International Laser Radar Conference in Annapolis, Md., along with other Hampton University graduate students and faculty. This premier international conference, rarely in the US, provided the students with a taste of atmospheric lidar research projects ongoing throughout the world. Numerous papers were presented on ozone lidar measurements.
- d. The success of this program, coupled with research ongoing in RCOP at HU and the Center for Atmospheric Sciences at HU, with the support of ITT and NASA Langley has led to the establishment of the Center for Lidar and Atmospheric Sciences Students (CLASS) at Hampton University.

2. Training of students in laser physics

- a. Mr. Christophe McCray, Ph.D. candidate, has been performing theoretical and experimental research on stimulated Raman scattering as a means to produce the ultraviolet laser energy needed for the lidar project. The results of his work have been presented at conferences and have been accepted for publication. In addition to working with faculty and postdocs at Hampton University, he has consulted with Mr. Waverly Marsh at NASA Langley Research Center and Dr. Karl Koch of Phillips Air Force Laboratory (Albuquerque) on theoretical and experimental aspects of the physics of Raman lasers.
- b. As part of the AURORA and UniPhy programs, the students involved in this project through those summer programs were taught a short course in laser physics and its application to optical remote sensing.

3. Integration with other Hampton University Outreach Programs

As mentioned, this project has provided research topics for HU's AURORA and UniPhy summer programs, and provides an ozone lidar instrument to complement the aerosol lidar system being designed and constructed by CLASS students. When completed, the ozone instrument will also be utilized as part of the CLASS outreach program to high school and middle schools.



Mr. Roosevelt Elivert, senior electrical engineering major, discusses his LabVIEW data acquisition program with Dr. Thomas Zenker.



Mr. Christophe McCray, Ph.D. candidate, develops a Raman laser for the ozone DIAL project.

Research Objectives for the Second Year

1. Laser Transmitter

- a. The chosen OPO laser will be engineered by ITT to fit within the system structure.
- b. Improvements to the OPO system will be theoretically evaluated and tested in the laboratory jointly by ITT (personnel, equipment, internal research funding) HU (students, faculty, equipment) and NASA LaRC (personnel, equipment).
- c. The solid state Raman laser technology will continue to be developed at HU and also in a joint HU-NASA LaRC laboratory experiment in the Remote Systems Technology Branch in the Aerospace Electronics Systems Division at NASA LaRC for possible use as a future laser source.

2. Lidar Receiver

- a. The fabrication of the optical receiver will be completed by ITT.
- b. Detectors will be chosen and purchased.
- c. The system will be aligned and tested.

3. Data Acquisition System

- a. HU students and faculty will continue to develop the LabVIEW software to control and diagnose the lidar system and to record, analyze and display the atmospheric measurements.
- b. The remaining components will be purchased and incorporated into the system.

4. System Integration

- a. The transmitter and receiver will be integrated into a lidar system structure.
- b. This system will be shipped to HU for integration with the data acquisition system.

5. Lidar Measurements of Tropospheric Ozone

- a. Ground testing of the system will be performed at HU.
- b. The system's performance will be evaluated with the system model.

6. Future Improvements and Applications

Beyond the second year of the grant, additional sources of funding will be sought to further improve the lidar instrument and to employ it in field campaigns sponsored by NASA or other agencies such as NOAA and the EPA. These agencies have already expressed interest in portable ozone lidar systems such as this one. System improvements may include increasing the range of the system to probe the stratospheric ozone layer and the inclusion of an aerosol channel to simultaneously measure atmospheric structure and particle loading.

This instrument would be a valuable addition to the CLASS program at Hampton University. If funds through CLASS can be identified to support students to improve and deploy this system, then a very powerful synergy would result between the scanning aerosol instrument built under CLASS and the ozone lidar. The CLASS instrument would enable the evolution of the atmospheric structure, particle loading, and transport to be studied in 3-D to provide an atmospheric context for the 1-dimensional ozone measurements possible with the ozone instrument. Eventually, the scanning technology developed for CLASS could be evaluated for use in the ozone lidar system.

Hampton University students will actively participate in these system improvements and field deployments. Engineers at ITT Systems and Sciences have expressed their desire to assist HU in obtaining further funding to jointly pursue these endeavors, and has offered to host HU students and faculty for joint research at ITT provided sources of funding to

support student travel can be identified. ITT will be hosting students for the CLASS project in forthcoming summers.

Educational Objectives for the Second Year

1. Training of students in laser remote sensing and atmospheric science

- a. This instrument, when completed, will be incorporated into the training received by the Center for Lidar and Atmospheric Sciences Students (CLASS) who are designing an aerosol lidar instrument. It could be utilized in the CLASS outreach program to Warwick High School and Crittendon Middle School.
- b. This instrument may be utilized as a demonstration experiment for the summer 1999 AURORA program at HU.
- c. Mr. Christophe McCray, Mr. Roosevelt Elivert (senior, electrical engineering), Ms. Brandi Thomas (junior, physics) and Ms. Crystal Toppin (junior, physics) will be involved in system testing and lidar measurements.

2. Training of students in laser physics

Mr. Christophe McCray, (physics Ph.D. candidate), will continue to perform experiments and theory on the solid state Raman laser for his Ph.D. dissertation project.

3. Training of students in computerized data acquisition and display hardware and software

Mr. Roosevelt Elivert (senior, electrical engineering), Ms. Brandi Thomas (junior, physics) Mr. Jason McNeil (junior, physics), and Ms. Crystal Toppin (junior, physics) will continue to develop LabVIEW software and hardware to control the instrument, and to record, analyze, and display the lidar measurements.

4. Integration with Hampton University outreach programs

This instrument will be utilized in the AURORA and UNIPhy 1999 summer programs to teach students about atmospheric science, laser remote sensing technology, lasers, optics, and engineering. Students in those programs will be part of system testing and atmospheric measurements with the instrument.

Presentations by Students

1. Thomas, B., R. Elivert, T. Zenker, and T. H. Chyba, "A data acquisition system for lidar measurements of ozone", Hampton University Third Annual Student Research Symposium, February 13-14, 1998.
2. McCray, C. L. and T. H. Chyba, "Stimulated Raman Amplification, Oscillation, and Linewidth Measurements in Barium Nitrate", NASA University Research Center Technical Conference, February 22-25, 1998, paper MLM2-4.
3. McCray, C. L., and T. H. Chyba, "Measurements of Stimulated Raman Amplification and Oscillation in Barium Nitrate", Advanced Solid State Lasers 1998, February 2-4, 1998, paper AME10.
4. Larson, D., T. Zenker, and T. H. Chyba, "LabVIEW Ozone Display Program", Hampton University Advanced Undergraduate Research Using Optical Radiation in the Atmosphere Research Day, July 24, 1998.
5. Toppin, C., T. Zenker, and T. H. Chyba, "Ozone Altitude Profile Error Analysis for Ozone Lidar Project", Hampton University Advanced Undergraduate Research Using Optical Radiation in the Atmosphere Research Day, July 24, 1998.

6. Thomas, B., T. Zenker, and T. H. Chyba, "Ozone Altitude Profile Data Analysis for the Ozone Lidar Project", Hampton University Advanced Undergraduate Research Using Optical Radiation in the Atmosphere Research Day, July 24, 1998.
7. McNeil, J., T. Zenker, and T. H. Chyba, "Development of a Computerized Energy Monitor for an OPO-Based Lidar System" Hampton University Undergraduate Institute in Physics-Research Experiences for Undergraduates Research Day, July 23, 1998.

Presentations by Faculty

1. Chyba, T. H., T. Zenker, C. L. McCray, H. R. Lee, B. Thomas, R. Elivert, N. S. Higdon, D. A. Richter, and J. Fishman, "Development of a compact ground-based ozone DIAL system", 19th International Laser Radar Conference, July 6-10, 1998, paper PS3.2-9
2. Zenker, T., T. H. Chyba, J. Fishman, N. S. Higdon, and D. A. Richter, "A compact ground-based uv lidar system for a global tropospheric ozone network", 1998 Symposium of the Commission on Atmospheric Chemistry and Global Pollution (CACGP) and the International Global Atmospheric Chemistry Project (IGAC), August 19-25, 1998.
3. Chyba, T. H., T. Zenker, C. L. McCray, H. R. Lee, B. Thomas, R. Elivert, N. S. Higdon, D. A. Richter, and J. Fishman, "A compact ground-based differential absorption lidar for measurements of tropospheric ozone", 1998 OSA Annual Meeting, October 4-9, 1998, paper WDD22.

Publications

McCray, C. M. and T. H. Chyba, "High Resolution Spectral Measurements of Raman Shifts in Barium Nitrate," Optical Materials, 11, 383-390, 1998.

McCray, C. M. and T. H. Chyba, "Measurements of stimulated Raman amplification and oscillation in barium nitrate," in Advanced Solid State Lasers, Technical Digest (Optical Society of America, Washington, D.C., 1998), pp. 139-141.

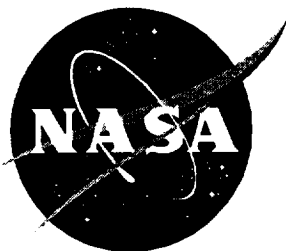
McCray, C. M., S. W. Lee, and T. H. Chyba, "Measurements of stimulated Raman amplification and Raman shifts in barium nitrate", OSA Trends in Optics and Photonics Vol. 19, Advanced Solid State Lasers, W. Bosenberg and M. M. Fejer, eds. (Optical Society of America, Washington, DC 1998), pp. 550-554.

Chyba, T. H., T. Zenker, C. L. McCray, H. R. Lee, B. Thomas, R. Elivert, N. S. Higdon, D. A. Richter, and J. Fishman, "Development of a compact ground-based ozone DIAL system", in Proceedings of the 19th International Laser Radar Conference, ed. by U.N. Singh, S. Ismail, and G. K. Schwemmer, (NASA Langley Research Center, Hampton, Va., 1998), pp. 779-782.

McCray, C. L. and T. H. Chyba, "Stimulated Raman Amplification, Oscillation, and Linewidth Measurements in Barium Nitrate", in NASA University Research Centers Technical Advances on Education, Aeronautics, Space, Autonomy, Earth, and Environment, Vol. 2, Proceedings of the NASA URC Technical Conference 1998 (ACE Center Press, Albuquerque, 1998), pp. 23-27.

Appendix 1. Copy of the article published in the Proceedings of the 19th ILRC

Appendix 2. Copy of poster presented at the 1998 OSA Annual Meeting



Nineteenth International Laser Radar Conference

Edited by
Upendra N. Singh and Syed Ismail
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Development of a Compact, Ground-Based Ozone DIAL System

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1. Introduction

We are developing a portable, eye-safe, ground-based ozone lidar instrument specialized for ozone differential absorption lidar (DIAL) measurements in the troposphere. This prototype instrument is intended to operate at remote field sites and to serve as the basic unit for future monitoring projects requiring multi-instrument networks, such as that proposed for the Global Tropospheric Ozone Project (GTOP). GTOP is currently being formulated by a scientific panel of the International Global Atmospheric Chemistry Project to meet its goal to better understand the processes that control the global distribution of tropospheric ozone [1]. In order for the lidar to be widely deployed in networks, it must be fairly easy to use and maintain as well as being cost-competitive with a ground station launching ozone sondes several times a day.

To achieve these goals, emphasis is placed upon the incorporation of (1) all-solid state transmitters which can reliably produce 20-40 mJ pulses, (2) a highly efficient, narrow-bandpass receiver, (3) dual analog and photon-counting detector channels, and (4) flexible, user-friendly control software.

2. Transmitter

Two candidate lasers are currently being evaluated as possible transmitters. Both are based upon mature Nd:YAG laser technology coupled with nonlinear frequency conversion chains to produce the wavelengths needed for differential absorption lidar measurements.

The first approach is based upon Raman shifting in solid-state crystals. It has the advantage of being very efficient and of producing well-defined wavelengths. However, the specific wavelengths produced are dictated by the Raman crystals utilized, so for compact systems this technique restricts the choice of wavelengths to two or three. The use of three wavelengths facilitates some optimization for the particular ozone distribution to be measured. Raman shifting a doubled Nd:YAG laser in an external cavity using barium nitrate and subsequent frequency doubling or mixing to the uv can produce 281.7 and 299.4 nm wavelengths. With a lithium iodate crystal, 289.8 and 303.3 nm pulses can be produced.

Figure 1 illustrates a 2-wavelength uv laser transmitter based upon Raman shifting in barium nitrate. The doubled output from a Q-switched Nd:YAG laser is split into two beams. One beam is mode-matched to a Raman oscillator and pumps it to produce a Raman-shifted output pulse at 599 nm. Residual energies at 563 nm (from the first Stokes shift) and at 532 nm are separated out with a dichroic mirror. The polarization of the 599 nm pulse is then rotated 90° by a Pockels cell and passes through a polarizing beam splitter. Its polarization is then rotated back and its wavelength is frequency doubled to 299 nm, producing the off-line pulse. To produce the on-line pulse, a timing circuit triggers the Pockels cell so that every other Raman pulse is not rotated in polarization. This unrotated pulse is reflected by the polarizing beam splitter. It is frequency-mixed with a portion of the 532 nm pump energy to generate the 282 nm pulse.

Our preliminary work with barium nitrate has demonstrated Raman conversion efficiencies exceeding 45% in the visible with a multimode pump [2]. Both off-line and on-line uv pulses have been produced in our laboratory, but with under 1 mJ pulse energies [3]. The low conversion efficiencies in the uv are due to a combination of high beam divergence from the Raman oscillator and low Raman oscillator energies. In the conference paper, we will present our current results with our redesigned oscillator and oscillator-amplifier configuration.

The alternative transmitter under laboratory evaluation is a Nd:YAG-pumped Type II optical parametric oscillator (OPO) frequency-doubled to the uv [4]. This laser has recently been reported to produce ~10 mJ pulses in the 300-nm region when pumped by 135 mJ of tripled output from an injection-seeded Nd:YAG. It has the advantage of tunability throughout the uv and can therefore be precisely wavelength optimized for a given ozone distribution. However, this also requires computer monitoring and control of the laser wavelength. It also increases the complexity of the wavelength masks in the focal plane of the receiver grating. In addition,

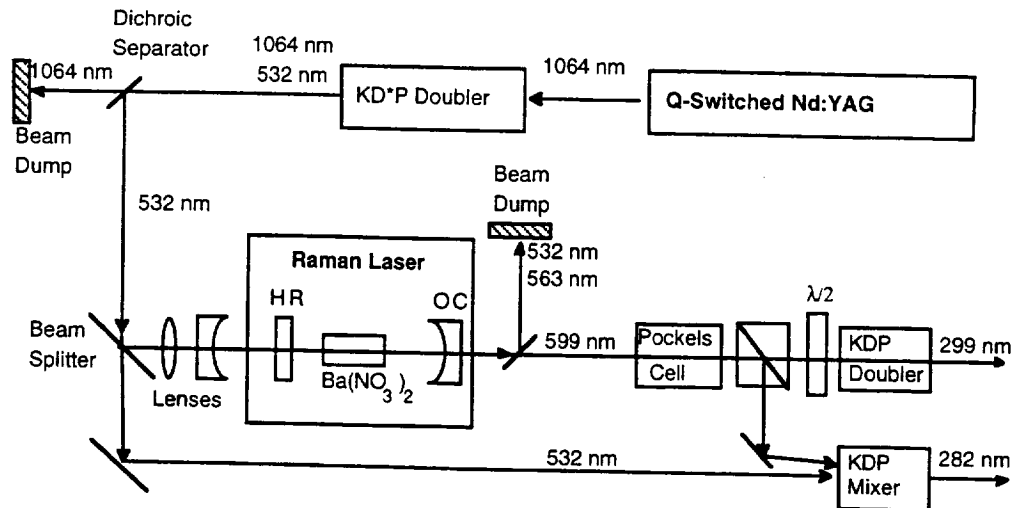


Figure 1. A candidate uv transmitter based upon a barium nitrate Raman oscillator

the injection-seeded pump laser increases the cost and complexity of the transmitter. Results for this laser will be presented in the conference paper.

3. Receiver

The lidar receiver utilizes a 12" square parabolic primary mirror and a grating-based spectrometer as a wavelength filter (Figure 2). Daylight prefiltering is performed by reflective dielectric coatings on the fold mirrors before the grating. For stock commercial triplet lenses and gratings, the bandpass in the focal plane of the grating is computed to be 2.4 nm for a single wavelength channel. By opening a shutter in the focal plane of the grating to allow through only the transmitted wavelength, the bandwidth can be maintained at 2.4 nm for a multi-wavelength system. With commercially available dielectric coatings, the throughput efficiency from the atmosphere to the detector plane is calculated to be ~60% for the far field (photon-counting mode) channel. The near-field (analog-mode) channel (not shown) will utilize the negative first order reflection from the grating and not reduce the efficiency of the far-field channel. A number of techniques are under investigation to address the problem of detector saturation and signal-induced bias due to the strong near field return.

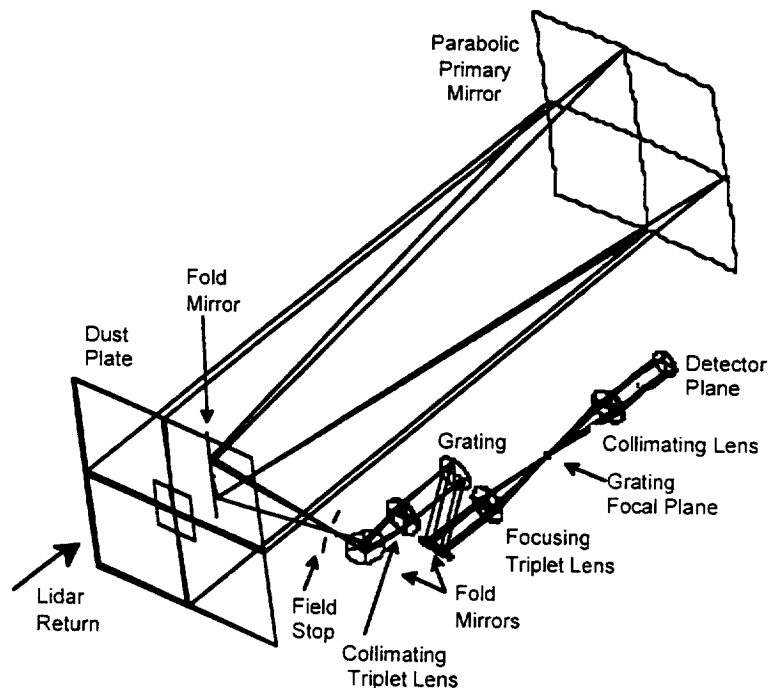


Figure 2. The lidar receiver optical layout.

Lightweight, graphite epoxy breadboards form the four walls of the telescope. The receiver and transmitter optics can be directly attached to two of these breadboards, making the entire system extremely compact.

The data acquisition system consists of a field-hardened personal computer with a 12-bit A/D and 300 MHz counter cards. Beam steering, system timing, and the monitoring of output pulse energies will also be computer controlled. The control and data analysis software is being written in LabVIEW.

4. Calculated Ozone DIAL performance

We have calculated the expected DIAL performance for our receiver and transmitter characteristics. As an example, we choose an ozone profile measured at the tropical ozone sonde station in Brazzaville, Congo, on day 294 in 1992 [5]. Using these data we simulate lidar return signals [6] accounting for Rayleigh scattering and extinction due to Rayleigh scattering and ozone absorption [7] for our chosen on- and off-line wavelength pairs: 281.7/299.4 nm and 289.8/303.3 nm for the Nd:YAG Raman transmitters and 286/299.4 nm for the Nd:YAG OPO-based system. The signal to noise (S/N) ratios for the DIAL return signal are calculated incorporating the contributions of several error sources: signal noise, sky background radiation for a sun zenith angle of 30°, dark current/counts of the photomultiplier tube (PMT), analog-to-digital resolution (10 usable bits for the analog mode), and the dead time error arising in the photon counting mode at high count rates. Figure 3 depicts the given ozone sonde profile and the calculated total S/N ratios of the far field (photon counting (PC)) channel and for two near field (analog) channels with different sets of operational parameters (A#1, A#2). Key parameters used for the calculations are listed in Table 1.

The S/N ratios shown in Figure 3 stay above ~10 for the shorter transmitter wavelength pairs over the entire tropospheric ozone profile, while S/N ratios drop below 10 for the 282/299 nm pair above an altitude of ~13 km. The latter pair shows a significantly higher sensitivity for the lower tropospheric ozone but becomes more insensitive for the upper free tropospheric ozone compared to the longer wavelength pairs.

The S/N ratio of the PC channel is primarily limited by signal noise, except above ~20 km and below ~8 km, where it is limited by dark count shot noise and dead time uncertainty, respectively. Below ~6.5 km the maximum anode current of the PMT is exceeded.

The analog channel A#2 shows sufficient overlap with the PC channel at reasonable S/N ratios but the measurements do not extend below ~1.8 km because the maximum allowed cathode current of the PMT is exceeded for reasonable PMT gain and ADC range settings. To allow lidar measurements down to 100 m, another analog channel (A#1) whose optical throughput is reduced by a factor of 5 relative to A#2 is needed. Two possible methods to cover the entire altitude range below 7 km with analog channels are: (1) operate two PMTs with a 20/80 beam splitter, or (2) record the lidar return alternatively with 20% transmission and full

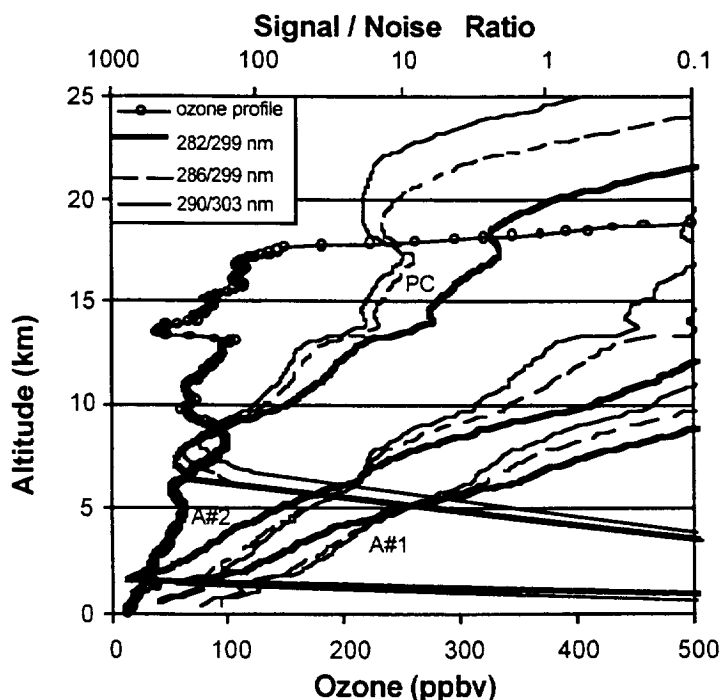


Figure 3. Simulated S/N ratios for the DIAL return computed for the plotted ozone sonde profile.

Table 1. Key parameters for the simulation of DIAL performance.

Transmitter	Transmitted energy, on/off-line Divergence, full angle	30/10 mJ 0.8 mrad
Receiver	Effective telescope area / diameter Total throughput PC channel (grating, order 1) Analog channel (grating, order -1) A#1 A#2 Field of view, full angle Bandpass for each wavelength	0.091 m ² / 13.4" 58.9% 0.29% 1.44% 1 mrad 2.4 nm
Photomultiplier Tubes	Hamamatsu H5600-6 series [8], Quantum efficiency Collection efficiency Rise time Dark anode current/count rate	 ~ 18% ~ 65% 0.65ns 0.5 nA/80 cnts/s
Range and time resolution	Photon counting channel Analog channel (A#1/A#2) # of pulses averaged, on- or off-line	1000 m 300/500 m 9000*

*this corresponds to a 30/10 min integration for a 10/30 Hz single-wavelength transmitter system.

sensitivity. The S/N ratios of the analog channels are limited by signal noise for S/N greater than ~5 and by dark current or ADC resolution for S/N lower than ~5.

For the system parameters in Table 1, shot noise due to sky background radiation is not expected to limit the lidar performance. In our calculations, a minimum constant background level on the PMT's is assumed for wavelengths shorter than 295 nm, corresponding to the apparent sky background for measurements taken at 295nm with a 2.4 nm optical bandwidth. The value of this minimum level is 10^{-6} W/m²/sr/nm, as measured with a typical telescope setup by Maeda *et al.* [9].

5. Summary

We are developing transmitter, receiver, and data acquisition technologies for a compact, ground-based ozone lidar system. An efficient, narrow-band receiver reduces the energies required for the laser transmitter to meet the measurement S/N objectives. Candidate laser transmitters are currently under evaluation. The current status of the system will be presented in the conference paper.

Acknowledgments

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A Compact, Ground-Based Differential Absorption Lidar for Measurements of Tropospheric Ozone

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Compact O₃ DIAL System Goals

- **Tropospheric Ozone Lidar Instrument**

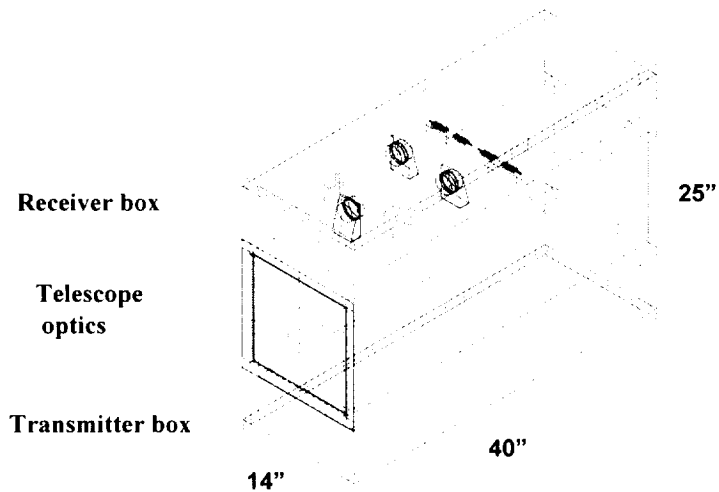
- compact, portable, eyesafe
- prototype candidate for ozone networks such as that proposed for the Global Tropospheric Ozone Project (GTOP)
- cost-competitive with regular ozonesonde launches with superior performance
- applicable to NASA and EPA programs

- **Educational Training and Outreach**

- promote goals of NASA Office of Equal Opportunity Programs, Minority University Research and Educational Division
- this prototype will be located at Hampton University for educational training and outreach.
- available for few months off-site measurement programs with emphasis on involving students in field work.

Compact O₃ DIAL Transceiver

3D-Layout



Compact O₃ System Design

Transceiver Structure &
Electronics Rack

- Points zenith and is capable of doing slant-path measurements for ground-based experiments
- Total volume estimated < 33 cubic feet
- Total weight < 250 pounds
- Power consumption estimated ~ 1.5 kW



Technical Approach

- Partnership with HU, NASA LaRC, & ITT
- Structure
 - light weight carbon fiber structure
 - transmitter, receiver and telescope modular integrated in common structure
 - separate small electronic rack
- Transmitter
 - all-solid state, compact
 - utilize minimal pulse energies and laser complexity needed to make scientifically valuable measurements
 - down select from several parallel R&D efforts
- Receiver
 - highly efficient coatings and grating-based filter
 - minimal weight and size
- DAQ
 - compact, rack mounted PC-based system
 - minimal requirements of only 2 PMT's, 1 dual-12Bit ADC and 1 photon counting card
 - user-friendly LabVIEW software for control, data analysis, and display

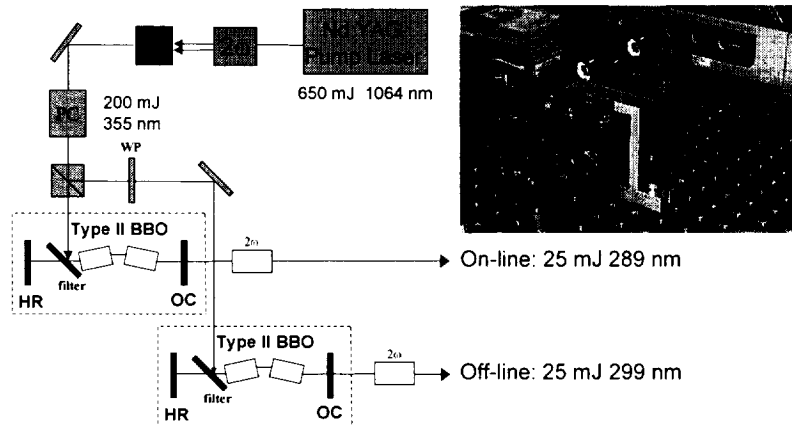
Compact O₃ DIAL Transmitter

Goals

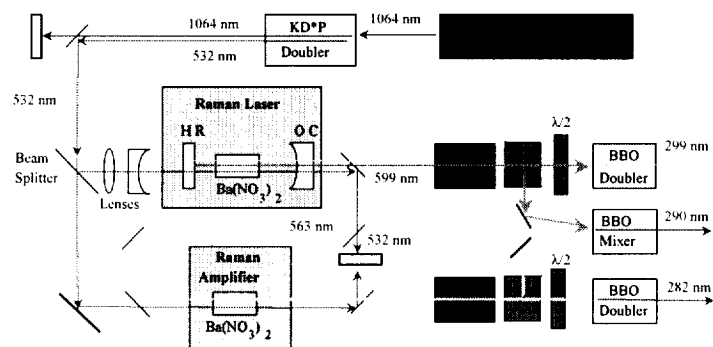
- All solid-state
- Compact
- Optically Efficient
- Field reliable
- Eyesafe
- Minimal complexity
- Minimal wavelength tunability
- Minimal energies necessary (>20 mJ)



Schematic Diagram of Doubled OPO Transmitter



Schematic Diagram of Solid-State Raman Transmitter



Singly Resonant Type II OPO Results

- Wavelength range 570-610 nm, limited by crystal apertures, doubled to 285-305 nm
- Seeded Nd: YAG results in > 55% energy conversion to the signal plus idler
- Unseeded Nd: YAG results in 25% conversion to the the signal plus idler
- Output energy for 220 mJ of 355 nm pump results in 22 mJ UV, a 10% CE Pump - UV

Solid-State Raman Laser Results

- High conversion efficiency
 - ~60% into the first and second Stokes combined
- High gain amplification of 1st Stokes
 - ~1500 from preliminary amplifier experiments
- Narrow linewidth with a single longitudinal mode pump
 - due to amplifier narrowing
- Low conversion into UV with present oscillator design
- Future research:
 - Redesigned resonator experiments
 - Oscillator/amplifier experiments
 - Optimization of uv conversion
- Goal is to provide a 2nd generation transmitter, more efficient than the 1st generation OPO transmitter

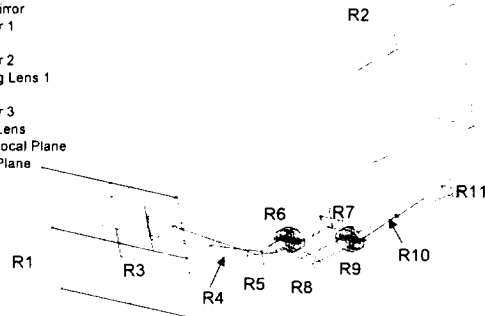
Compact O₃ DIAL Receiver

Design Features

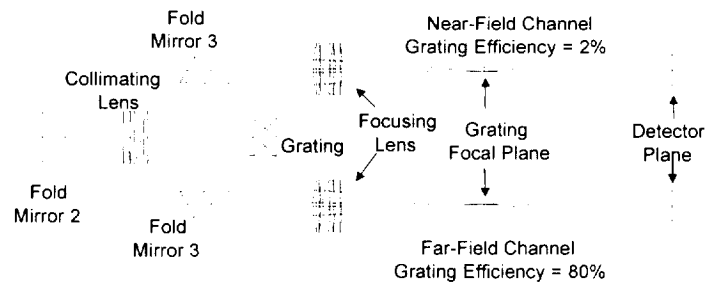
- High efficiency UV grating with enhanced reflectivity coating
- Near-field and far-field channels utilizing both +/- 1 orders
- Highly efficient dielectric coatings on all surfaces
- Integral telescope, receiver, and transmitter
- Square form- factor mirror to minimize volume
- Light-weight carbon fiber benches with aluminum honeycomb
- Light-weight primary mirror < 5 lbs
- Proprietary fast shutter technology to maximize dynamic range
- Low aberration imaging produces < 2.6 nm band-pass

Receiver Optics--Far Field Channel

- R1: Dust Plate
- R2: Primary Mirror
- R3: Fold Mirror 1
- R4: Field Stop
- R5: Fold Mirror 2
- R6: Collimating Lens 1
- R7: Grating
- R8: Fold Mirror 3
- R9: Focusing Lens
- R10: Grating Focal Plane
- R11: Detector Plane



Far Field and Near Field Channels



Receiver, Key Specifications

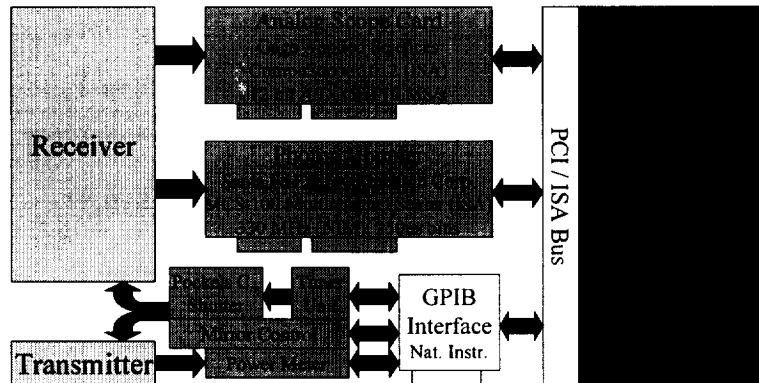
- | | |
|--------------------------------|--|
| • Telescope Area | 12" x 12" squared
(corresponds to 13.5" diameter) |
| • Focal Length | 42" |
| • Receiver Transmission: | |
| far field | 65% |
| near field | 1.6% |
| • Field of View (designed for) | 1 mrad full angle |

Compact O₃ DIAL DAQ

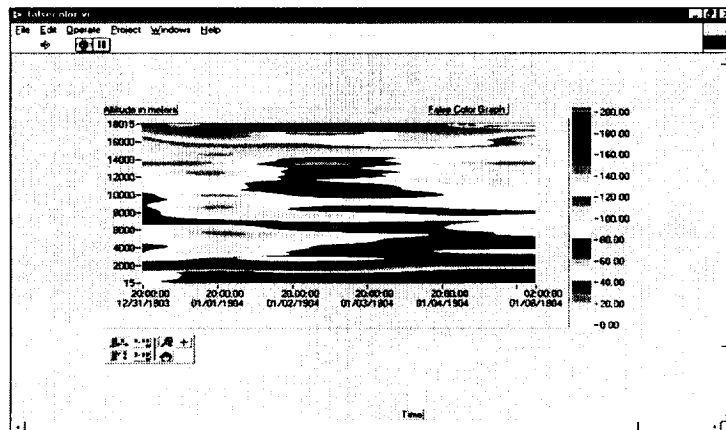
- Two Hamamatsu mini-PMT's
- One Dual channel A/D card
- One photon counting card
- One programmable I/O card
- Rackmounted PC-based system
- LabVIEW software



DAQ Schematic



False Color Plot: LabVIEW Front Panel



[illegible]

- Different ozone sonde profiles with baseline and enhanced ozone concentrations from several ozone sonde stations have been used to simulate the system performance.
- The DIAL signal to noise ratio (S/N) is calculated using system model parameters to evaluate the system performance.
- Noise sources which are evaluated and propagated through the DIAL equation to estimate the expected uncertainty in the ozone concentration are:
 - signal shot noise, dark current /counts, sky background shot noise, dead time uncertainties (photon counting channel)

Model System Parameters

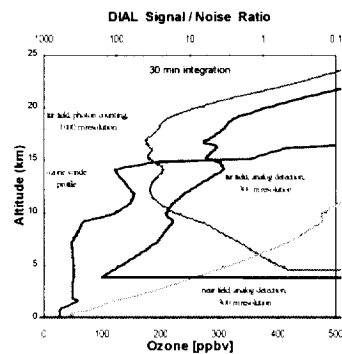
Transmitter	
Pulse Power, on/off-line	25 / 10 mJ
Repetition rate	20 Hz, single wavelength pulses
Wavelength, on/off-line	290 / 300 nm or 285 / 300 nm
Receiver	
Telescope area	12" x 12"
Bandwidth for each wavelength	2.6 nm
Receiver transmission near / far field	1.6 % / 65 %
Field of View	1 mrad full angle
Detection mode, near / far field	Analog / Photon counting
PMT	Standard specifications of Hamamatsu H56xx mini tube series (e.g., QE=18%, noise excess factor = 1.92)
Photon counting dead time	3 ns (5% error assumed) (330 MHz counter, 3x PMT rise time = 1.8ns)
Sky background	30 degree zenith angle, minimum stray light at PMT: 10^{-6} W/sr/m ² /nm
Atmosphere	
Rayleigh and ozone extinction, Aerosol extinction assumed in planetary boundary layer (PBL) depending on location	

Simulation for Wallops Island, Virginia USA

- Transmitter: $\lambda_{\text{on-line}} = 290$ nm, $\lambda_{\text{off-line}} = 300$ nm
- Aerosol extinction assumption:
1.5 km PBL height with $\kappa = 3 \cdot 10^{-4} \text{ m}^{-1}$

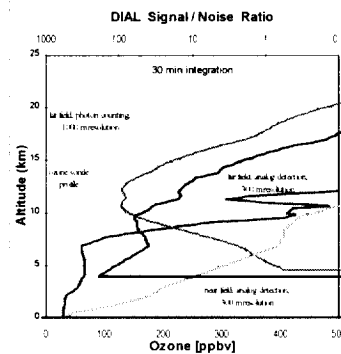


Simulated HU-DIAL Errors for Ozone
@ Wallops Island, VA (USA), 1992_96



Winter profile with high tropopause
and upper level pollution.

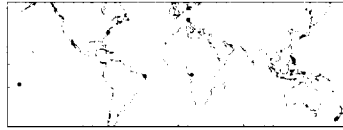
Simulated HU-DIAL Errors for Ozone
@ Wallops Island, VA (USA), 1992_93



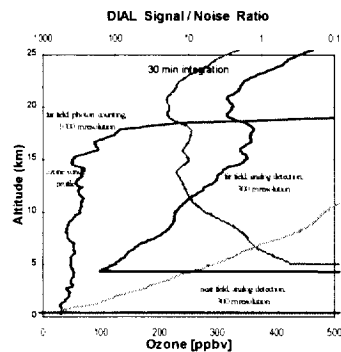
Spring profile with
tropopause folding.

Simulation for Brazzaville, Congo

- Transmitter: $\lambda_{\text{on-line}} = 290 \text{ nm}$, $\lambda_{\text{off-line}} = 300 \text{ nm}$
- Aerosol extinction assumption:
1.5 km PBL height with $\kappa = 3 \cdot 10^{-4} \text{ m}^{-1}$

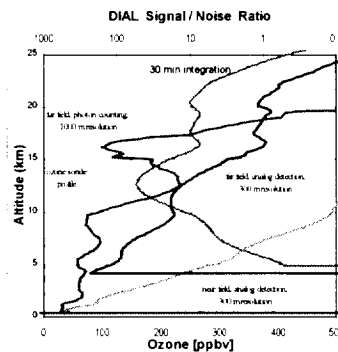


Simulated HU-DIAL Errors for Ozone
@ Brazzaville, Congo, 1992_48



Winter profile with low ozone.

Simulated HU-DIAL Errors for Ozone
@ Brazzaville, Congo, 1992_265



Fall profile, enhanced ozone likely
from biomass burning activity.

Conclusions

O₃ DIAL Performance Simulation

- Sufficient S/N within 30 min integration with range resolution between 200m and 1km between lower and upper troposphere, respectively.
- Measurement capability up into the lower stratosphere, in several cases reaching the ozone maximum of the stratospheric ozone layer. Typical DIAL ranging 0-22 km compared to sondes 0-30 km.
- Superior capabilities compared to ,e.g. even daily sonde measurements:
 - study of diurnal tropospheric ozone profile developments
 - higher accuracy in ozone trend monitoring
 - study of tropopause foldings

O₃ DIAL System Status

- Overall system conceptual design complete
- OPO laser chosen for transmitter
 - pulse energy and tunability demonstrated
 - dual wavelength transmitter to be tested
- Raman laser development to continue
 - possible second generation transmitter
- Receiver under construction
 - high efficiency, narrow bandpass
- DAQ hardware being tested
- DAQ software being written
- Performance model predicts high S/N

Future Work

- Fall/Winter 1998
 - Subsystem assembly and testing
- Winter/Spring 1999
 - System Integration
- Spring/Summer 1999
 - Ground Tests

Acknowledgements

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